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A SIMPLE METHOD FOR DETERMINING HIGH HEAT RATES BY USING SLUG CALORIMETERS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1967

N72-73337

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SUMMARY

The possibility of using a single thermocouple slug calorimeter in applications where the magnitude and duration of heating require a thick slug having appreciable internal temperature gradients is discussed herein. A 0.508-centimeter-thick beryllium slug calorimeter was subjected to heating rates in the range of 100 to 1100 watts/cm^2 for periods up to 2 seconds at the higher rates and for periods up to 20 seconds at the lower rates. It was found that the equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$ (where $\dot{q}$ is heating rate, l is the length of the calorimeter, ρ is density, c is specific heat, T is temperature, and t, time) would yield heat-rate values to within 5 percent of the input provided the temperature measurements were made at a distance from the back face of the slug equal to 60 percent of the calorimeter length. This condition held true for a variety of inputs, both constant and varying, obtained from analytical studies, ground tests, and flight data. The simplicity of this method, requiring a single-point measurement per calorimeter, could substantially reduce the time and costs involved in investigations of high heat rate.

INTRODUCTION

In the present program of reentry heat-transfer investigations the problem of heat-rate measurement requires a sensor capable of absorbing high heat rates over relatively long periods of time (seconds). If a slug calorimeter is used, the material must have enough thermal capacity to prevent melting during the test period. Thus the slug must be relatively thick since it will experience large temperature gradients. These requirements, plus the variation of the thermal properties of the slug with temperature, have made the measurement difficult to treat simply and have resulted in the use of complex and time-consuming techniques. In the Project Fire program (ref. 1), beryllium calorimeters were instrumented with four thermocouples (0.025-mm-diameter chromel-alumel wire insulated by 0.10-mm o.d. double-bore quartz tubing) which were installed at various depths from the slug face (fig. 1). From the four temperature measurements, the thermal energy storage rate within the calorimeter was obtained. After adding terms for losses

[redacted]

from the front and back faces of the calorimeter, the heat rate input, $\dot{q}$, was determined. This procedure is called "inverse method." Since most methods used for determining high heat rates of long duration require similar multitemperature measurements and curve-fitting procedures, an effort was made to find a method that would simplify the instrumentation and data reduction. If the one-dimensional heat-flow problem is considered when the losses are small (approximately 2 percent), the input heat rate can be determined by applying measurements from a single thermocouple to the equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$. This paper reports on an investigation of the feasibility of such an approach using a 0.508-centimeter-long beryllium calorimeter.

SYMBOLS

c	specific heat, watts-sec/g/$^{\circ}$K
k	thermal conductivity, watts/cm-$^{\circ}$K
l	length of calorimeter, cm
n	integer
$\dot{q}$	heat rate, watts/cm^2
T	temperature, $^{\circ}$K
t	time, sec
x	distance from back face into calorimeter, cm
α	thermal diffusivity, cm^2/sec
ρ	density, g/cm^3
τ	response time, sec

Subscripts:

av	average
in	input

THEORY AND COMPUTER ANALYSIS

For the case of one-dimensional heat flow, the calorimeter is considered to be a solid bounded by a pair of parallel planes at $x = 0$ and $x = l$. The solid is heated uniformly at $x = l$ with a constant input and with no heat loss. By considering the initial temperature to be zero and the thermal parameters to be constant, Carslaw and Jaeger derived the following equation (ref. 2):

$$T = \frac{\dot{q}t}{\rho c l} + \frac{\dot{q}l}{k}\left[\frac{3x^2 - l^2}{6l^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-\alpha n^2\pi^2 t/l^2}\cos\left(\frac{n\pi x}{l}\right)\right] \tag{1}$$

where T is the temperature rise above the initial temperature. The symbols used by Carslaw and Jaeger with the equivalent symbols used in this paper are as follows: $v = T$, $F_O = \dot{q}$, $K = k$, and $\kappa = \alpha$. Differentiating equation (1)

$$\frac{dT}{dt} = \frac{\dot{q}}{\rho c l} + \frac{2\dot{q}l}{\pi^2 k}\left[\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\frac{\alpha n^2\pi^2}{l^2}e^{-\alpha n^2\pi^2 t/l^2}\cos\left(\frac{n\pi x}{l}\right)\right] \tag{2}$$

When t becomes large enough, the second term on the right side of the equation becomes negligible compared with the first term, and equation (2) reduces to

$$\dot{q} = l\rho c\frac{dT}{dt} \tag{3}$$

Since equation (3) depends upon constant thermal parameters, a computer program (ref. 3) was run to determine the feasibility of using this method in the practical case where the thermal parameters are not constant. The program provided for a step input, for variation of thermal conductivity and specific heat with temperature, and for losses from both the front face by reradiation (Emittance = 0.97) and from the rear face by conduction to air. The program was run for beryllium and copper calorimeters. From the curves of the variation of temperature with distance computed at various times, the equation $\dot{q} = l\rho c\frac{\Delta T}{\Delta t}$ was used to obtain the heat rates. In figure 2 (for an input of 680 watts/cm^2), the accuracy of determining $\dot{q}$ was found to depend on the thermocouple location – the optimum location occurred between $0.72l$ and $0.47l$. To minimize the transient effect, the time of measurement was found to be at $t \geqq 0.5$ second. For a span of $0.25l$ about the $0.6l$ location in the beryllium slug, measurements would fall within 5 percent of the input value. For an input of 680 watts/cm^2 to a copper calorimeter, measurements would fall within 1 percent of the input value at times as short as 0.15 second (fig. 3) which is due to the greater diffusivity of copper.

If the data that were used in figures 2 and 3 were plotted as the variation of $\dot{q}$ with distance in the slug, the curves converge and become essentially parallel (figs. 4 and 5). This convergence indicates that the transient effect has become negligible when the curves attain similar shapes (approximately 0.5 sec for Be and 0.15 sec for Cu).

If an average or effective temperature could be determined and shown to occur at a particular location, a temperature measurement made at this point would yield an average specific heat to be used in the equation $\dot{q} = l\rho c \frac{\Delta T}{\Delta t}$. This measurement can be made when the specific heat is a linear function of temperature over the range established by the temperature gradient in the calorimeter. If the average temperature is changing at an average rate (average $\Delta T/\Delta t$), enough data are obtained at this point to determine the correct $\dot{q}$ after allowing for transient effects to subside and assuming that $l\rho$ is essentially constant. This average temperature may be defined as

$$T_{av} = \frac{1}{l}\int_0^l T(x)dx$$

from equation (1)

$$T_{av} = \frac{1}{l}\left[\int_0^l \frac{\dot{q}t}{\rho c l}dx + \int_0^l \frac{\dot{q}L}{k}\left(\frac{3x^2 - l^2}{6l^2}\right)dx - \frac{2\dot{q}l}{k\pi^2}\int_0^l \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-\alpha n^2\pi^2 t/l^2}\cos\left(\frac{n\pi x}{l}\right)dx\right]$$

$$T_{av} = \frac{1}{l}\left[\frac{\dot{q}tl}{\rho c l} + \frac{\dot{q}l}{k}(0) - \frac{2\dot{q}l}{k\pi^2}(0)\right]$$

$$T_{av} = \frac{\dot{q}t}{\rho c l} \tag{4}$$

and

$$\frac{dT_{av}}{dt} = \frac{\dot{q}}{\rho c l} \tag{5}$$

The equivalence of equation (5) to equation (3) shows that the time derivative of the average temperature is a constant, independent of time, and after the transient period is over, the time derivative of the temperature is independent of position. To determine the location of the average temperature, equation (4) is substituted in equation (1) and the resulting equation is solved for x as follows:

$$\frac{\dot{q}t}{\rho c l} = \frac{\dot{q}t}{\rho c l} + \frac{\dot{q}l}{k}\left[\frac{3x^2 - l^2}{6l^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-\alpha n^2\pi^2 t/l^2}\cos\left(\frac{n\pi x}{l}\right)\right]$$

$$\frac{3x^2 - l^2}{6l^2} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-\alpha n^2\pi^2 t/l^2}\cos\left(\frac{n\pi x}{l}\right) \tag{6}$$

When the transient becomes negligible (i.e., when t is large enough for the right side of equation (6) to be considered zero), the location of the average temperature becomes constant and is found as follows:

$$\frac{3x^2 - l^2}{6l^2} = 0$$

$$x = \frac{l}{\sqrt{3}} = 0.578l \tag{7}$$

as measured from the back face.

For a gage length of 0.508 cm, the average temperature would be located 0.294 cm from the back face. A thermocouple at this point will give the correct temperature needed to find the c and $\Delta T/\Delta t$ to be used in the equation $\dot{q} = l\rho c \frac{\Delta T}{\Delta t}$. In determining the location of the average temperature and the average rate of change of temperature, the thermal parameters were assumed to be constant with temperature. Since this assumption is not true, the foregoing discussion may seem academic until this location of average temperature is compared with the location of average temperature determined from data obtained from the computer program (fig. 6). When c and k are allowed to vary with temperature (as in the computer program), the average values of temperature and $\Delta T/\Delta t$ are located at approximately $x/l = 0.6$, although $\Delta T/\Delta t$ departs markedly from the constant value predicted by equation (3) (figs. 6 and 7).

Because of the requirement that the transient disappear before valid data can be obtained, a characteristic minimum elapsed time is necessary to predict the calorimeter performance. Such a time may be defined as

$$\tau = \frac{2l^2}{\pi^2\alpha} \tag{8}$$

At this value of τ it can be shown, by using equations (1) and (2), that the temperature is within 4 percent of the value predicted by equation (4) and that dT/dt is within 8 percent of the rate indicated by equation (5). Using these values in equation (3), $\dot{q}$ is determined with an approximate error of 5 percent.

Since α is a function of temperature, the actual response time of the calorimeter depends on the temperature rise during the transient period which in turn depends on the input. In the case of the beryllium calorimeter described in this paper, a reasonable estimate of τ can be made in the following manner:

(1) Evaluate τ in equation (8) by using ambient values for the thermal parameters.

(2) Evaluate T_{av} in equation (4) by using $t = \tau$ from step (1).

(3) Using T_{av}, find the proper value of α to reevaluate τ.

(4) Reevaluate τ in equation (8) by using α found in step (3).

The calorimeter response time calculated by this method is 0.13 second. The $\dot{q}$ computed from equation (3) with data obtained from the computer program at $t = 0.13$ second is within 2.5 percent of the $\dot{q}$ used in this program (896 watts/cm^2). This value compares with an error of 6.5 percent if an α evaluated at ambient temperature were used to find τ (0.093 second). In every application, care should be taken to consider the temperature sensitivity of the particular slug material and the expected input when estimating the response time of the calorimeter.

GROUND TEST PROCEDURE

To obtain heating rates in the range of 550 to 900 watts/cm^2, an arc imaging furnace (ref. 4) was used. The optical system included a 5.08-centimeter-diameter field stop, a shutter to obtain step inputs, and wire screen filters to vary the heat input. (See fig. 8.) A metal mask was used to prevent radiant energy from heating the sides of the calorimeter. Both solar cells and shutter contacts were used to determine the shutter times. The solar cells also indicated the variation of radiant intensity with time. A block diagram of the instrumentation is shown in figure 9. The front faces of the calorimeters were coated with a camphor black that has a reflectivity of approximately 3 percent over the spectral region of interest. The calorimeters were placed in an insulated thin V block and held in place with a piece of insulated spring steel. This configuration allowed a heat loss from the calorimeter to the holder that was small compared with the losses at the back face. The calorimeters were positioned in the focal area by using a grain of wheat lamp in place of the arc anode. The following procedure was used in a typical test: The arc was struck and stabilized, the douser was opened, the control-box switch was thrown to provide the sequential operation of the recorder and the shutter, and finally, the douser was closed and the arc extinguished. Successive calibrations of a beryllium calorimeter were run both without a filter (run 1) and with filters of decreasing transmissions (runs 2, 3, and 4).

ANALYSIS OF GROUND TESTS

From the thermocouple data, temperature and $\Delta T/\Delta t$ gradients were plotted, and the locations of the average temperature and average $\Delta T/\Delta t$ were determined by mechanical integration. In all cases, the location of these average values ($\cong 0.60l$) agreed closely with the calculated location of $0.578l$ (figs. 10 and 11).

The effects of the transient were checked by applying the thermocouple data to the expression $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$ and plots of $\dot{q}$ against time for runs 1, 2, 3, and 4 were plotted (figs. 12 to 15). Since the curves appear to flatten after 0.5 second, data after this time were used to obtain a plot of evaluated $\dot{q}$ against input $\dot{q}$ (fig. 16). The maximum losses were estimated to be approximately 1 watt/cm^2 due to radiation from the front face and 6 watts/cm^2 due to conduction from the back face. The arc-image furnace was calibrated to determine the input $\dot{q}$ by using a water-cooled calorimeter.

COMPARISON WITH FLIGHT-TEST RESULTS

The variations of temperature with depth and temperature with time were plotted from data obtained in the Project Fire reentry flight tests (ref. 1). Heat rates were determined by using the equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$. The values of c and $\Delta T/\Delta t$ were obtained by using the temperature taken at a point $0.60l$ from the back face of the calorimeter. The flux rates were then corrected for radiation and conduction losses by using the estimated values from reference 1. A comparison of these heat rates and the heat rates found by the Project Fire "inverse method" is shown in figure 17 and agrees generally to within 5 percent.

RESULTS

Temperature measurements made at a point $0.60l$ from the back face of a beryllium calorimeter are sufficient to determine the input heat rates by using the equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$. The determination of $\dot{q}$ was shown theoretically and experimentally to agree within 5 percent of the input value for step inputs (fig. 16). For the varying inputs which were experienced in the Project Fire 1 flight test, the values of $\dot{q}$ obtained by this simple method agreed generally within 5 percent with the values of $\dot{q}$ determined by the "inverse method" (fig. 17). For step inputs, it has been shown theoretically and experimentally that the average temperature and the average $\Delta T/\Delta t$ occur at approximately the same location in a beryllium calorimeter (figs. 6, 7, 10, and 11). The sensitivity to thermocouple positional error decreases with increasing thermal diffusivity because, for a given input, materials with the greater diffusivities would have smaller temperature gradients (figs. 2 and 3).

DISCUSSION

The usefulness of the method which utilizes the simple equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$ depends on certain conditions which should be carefully examined. The conditions are as follows:

(1) The variation of thermal diffusivity with temperature must be such that the average temperature and average $\Delta T/\Delta t$ occur at a single fixed point.

(2) The average temperature must define the average specific heat of the calorimeter.

(3) The losses are small.

(4) For step inputs, enough time must have elapsed for the transient effect to become negligible.

(5) Melting does not occur.

The first condition is necessary because single-point temperature measurements are used to describe the behavior of the entire calorimeter. The average temperature is used to determine the average or effective value of c. Since a thermocouple indicates the temperature at a fixed point, the average temperature must remain at this point or the determination of c will be in error. Similarly, the average or the effective value of $\Delta T/\Delta t$ must remain at this same point. From data which were obtained from tests and a computer program, the location of the average temperature and the average $\Delta T/\Delta t$ was found to be at a location of approximately $0.60l$ as measured from the back face of the beryllium calorimeter.

For the average specific heat to be determined by the average temperature of the calorimeter, the specific heat should vary linearly with temperature. If this is not true, these average values will not occur at the same location in the calorimeter, and the use of a single thermocouple may not suffice. The fact that the specific heat need only be linear over the temperature difference existing in the calorimeter at the time of measurement relaxes this requirement somewhat. Some metals have a specific heat which varies linearly with temperature over the greater part of the range from ambient to the melting point (e.g., Ag, Cu, Al, Pt, and Mg). Other metals are nonlinear at the lower temperatures and become linear as the temperature increases (e.g., Be, Ta, Ti, Mo, Inconel, and stainless steel). Each material considered should be investigated thoroughly to determine its suitability for the intended application.

Because equation (3) indicates the thermal-energy storage rate, the heat loss should be small (approximately 2 percent) to retain accuracy. The shape and the magnitude of the temperature gradient in the calorimeter depends upon the magnitude of the thermal diffusivity and its variation with temperature. If the losses become so excessive that they affect the shape of the temperature gradient curve, the location of the average values of T and $\Delta T/\Delta t$ will change. Although the amount of error for a certain shift in these average values is not discussed in this paper, a computer program could be written to simulate any desired losses. Using the computer program with an input of 1034 watts/cm^2 and losses of approximately 1 percent, the temperature gradient in the beryllium calorimeter was 210° K with a maximum temperature of 725° K at 0.578 second. Under these conditions, an error of $\pm$0.025 cm (approx. $0.10l$) in location of the thermocouple would result in a 2-percent error in the determination of $\dot{q}$. This positioning error is proportional to the magnitude of the gradient which depends on the losses and the heat input.

For step inputs, the shape of the temperature gradient in the calorimeter varies drastically at first and then becomes essentially constant after a period of time (figs. 4 and 5). An estimate of this time, the response time of the calorimeter, can be made by evaluating τ in equation (8) and correcting for the temperature dependence of thermal diffusivity. After this time, the average temperature and average $\Delta T/\Delta t$ does not change location appreciably ($x/l \approx 0.6$).

When the calorimeter starts melting, equation (3) can no longer be used since the two existing states, liquid and solid, have different thermal properties and varying lengths.

This paper describes the behavior of beryllium and copper calorimeters only, and the extension of this method to other materials should be undertaken with caution. The thermal diffusivity is of primary importance since it determines (1) the positioning of the average temperature and $\Delta T/\Delta t$ in the calorimeter, (2) the magnitude of the temperature differential through the calorimeter, and (3) the response time of the calorimeter. The linearity of the curve of specific heat plotted against temperature indicates the possibility of using the average temperature to determine the average specific heat. The length of the calorimeter provides some flexibility in design and can be varied to fit the requirements of a particular problem. In table I various materials are listed with an indication of how their thermal properties vary over the temperature range from 278° to 833° K. These materials have not been studied in detail for this application but, by inspection, appear to have the possibility for use as simple slug calorimeters. Some points of interest are the effects of the discontinuities occurring in the thermal properties of iron and titanium, the increase in conductivity with temperature in tantalum and niobium, and the limitations imposed by the low thermal diffusivities of Inconel X and 310 stainless steel. When the preceding conditions are met, the method should be suitable for heat rates greater than the maximum measured rate of 1130 watts/cm^2 reported in this paper.

CONCLUSIONS

It has been shown both theoretically and experimentally that the output of a single thermocouple placed at 60 percent of the length of the calorimeter in a beryllium slug calorimeter can yield sufficient information to determine heat rates in the range from 120 to 1130 watts/cm^2 when the equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$ is used ($\dot{q}$ is heat rate, l is length of calorimeter, ρ is density, c is specific heat, T is temperature, and t is time). Results obtained by using this method have agreed to within 5 percent of both those made by a water-cooled calorimeter in ground tests and those made with flight-test data using a multithermocouple approach for determining $\dot{q}$. Although the maximum measured heat rate was 1130 watts/cm^2, this method should be valid for higher heat rates, subject to certain restrictions. Since the time response is determined by the length of the calorimeter and the thermal diffusivity, which varies with temperature, the calorimeter response will change with temperature. The material and size of the calorimeter would depend upon the test conditions and the requirements of the experiment. Since this approach requires the installation of only one thermocouple per calorimeter and the fundamental equation $\dot{q} = l \rho c \frac{\Delta T}{\Delta t}$ is applicable, this technique can greatly simplify the problems of data acquisition and data reduction in high heat-rate investigations particularly in flight applications requiring a large number of calorimeters.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 20, 1966,
125-24-03-04-23.

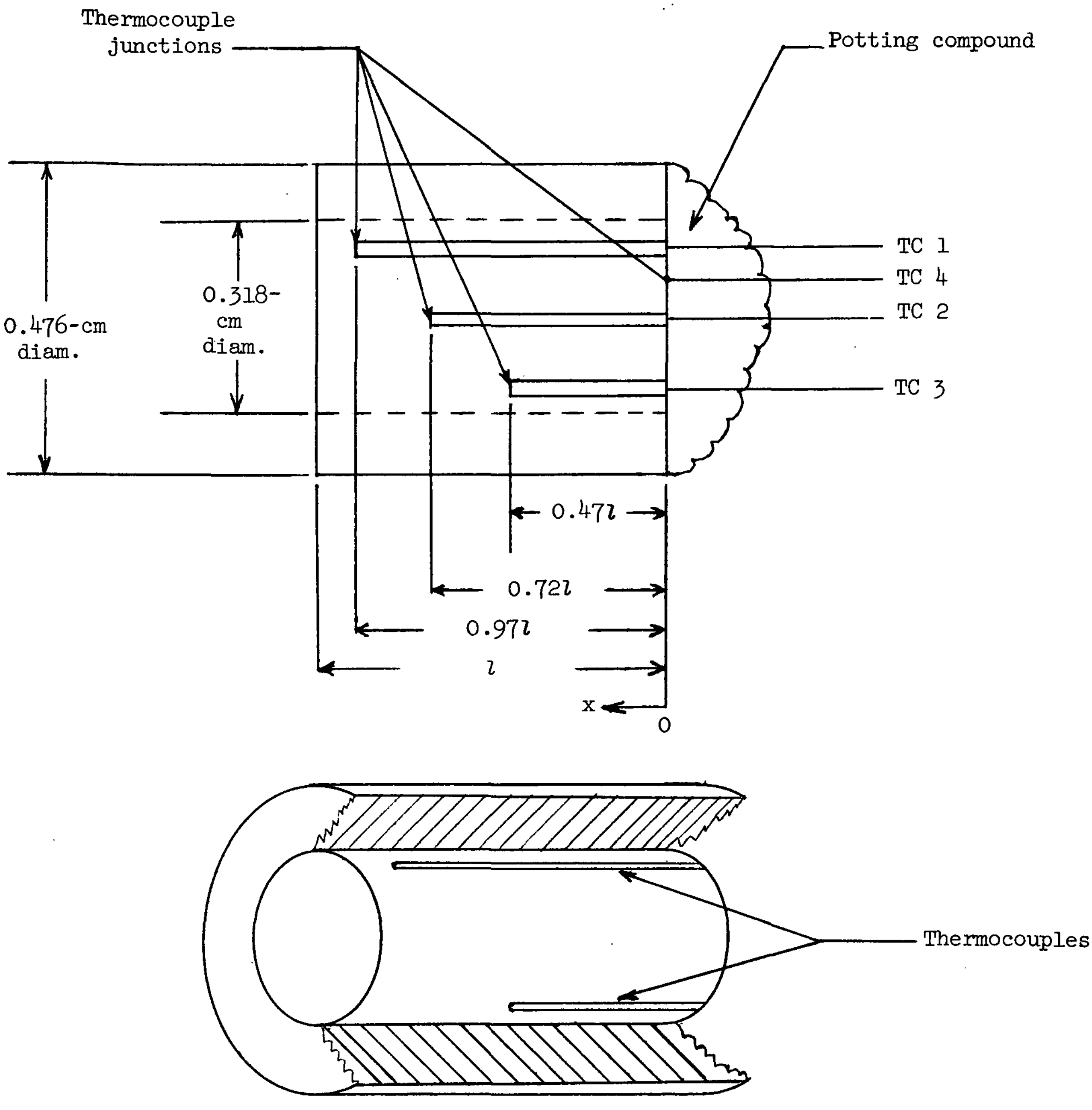
REFERENCES

1. Cornette, Elden S.: Forebody Temperatures and Total Heating Rates Measured During Project Fire 1 Reentry at 38 000 Feet Per Second. NASA TM X-1120, 1965.
2. Carslaw, H. S.; and Jaeger, J. C.: Conduction of Heat in Solids. Second ed., Oxford Univ. Press, Inc., 1959.
3. Swann, Robert T.; and Pittman, Claud M.: Numerical Analysis of the Transient Response of Advanced Thermal Protection Systems for Atmospheric Entry. NASA TN D-1370, 1962.
4. Comstock, Daniel F., Jr.: Method for Temperature and Reflectance Determination in an Arc-Imaging Furnace. Temperature – Its Measurement and Control in Science and Industry. Reinhold Pub. Corp., c.1962, pp. 1063-1071.
5. Goldsmith, Alexander; Waterman, Thomas E.; and Hirschhorn, Harry J.: Thermophysical Properties of Solid Materials. Volume I: Elements. Rev. ed., The Macmillan Co., 1961.

TABLE I.- MATERIALS WITH MELTING POINTS ABOVE 900° K

[Data from ref. 5]

Name or symbol	ρ, g/cm3 at:		k, watts/cm-°K at:		α, cm2/sec at:	
	278° K	833° K	278° K	833° K	278° K	833° K
Ag	10.4	10.1	4.22	3.41	1.74	1.29
Au	19.3	18.7	3.46	2.99	1.42	.955
Cu	8.93	8.68	4.08	3.51	1.18	.903
Al	2.70	2.59	2.28	1.83	.949	.593
Molded graphite	1.73	1.73	1.28	.779	.885	.283
Mg	1.74	1.66	1.38	1.33	.789	.616
Be	1.85	1.79	1.88	.900	.606	.175
Mo	10.2	10.1	1.36	1.19	.513	.418
Cr	7.16	7.04	.900	.692	.286	.172
Ta	16.5	16.3	.623	.692	.273	.260
Pt	21.4	21.1	.709	.685	.255	.222
Fe	7.88	7.73	.744	.398	.225	.072
Nb	8.57	8.45	.450	.528	.219	.214
Ti	4.59	4.56	.225	.173	.092	.059
Inconel X	8.24	8.04	.145	.232	.041	.051
310 stainless steel	7.84	7.62	.145	.193	.033	.044



Pictorial view

Figure 1.- Multithermocouple slug calorimeter. Thermocouples placed around the surface of the inner cylinder and spaced 120°, with one thermocouple in the center of the back face. l = 0.508 cm.

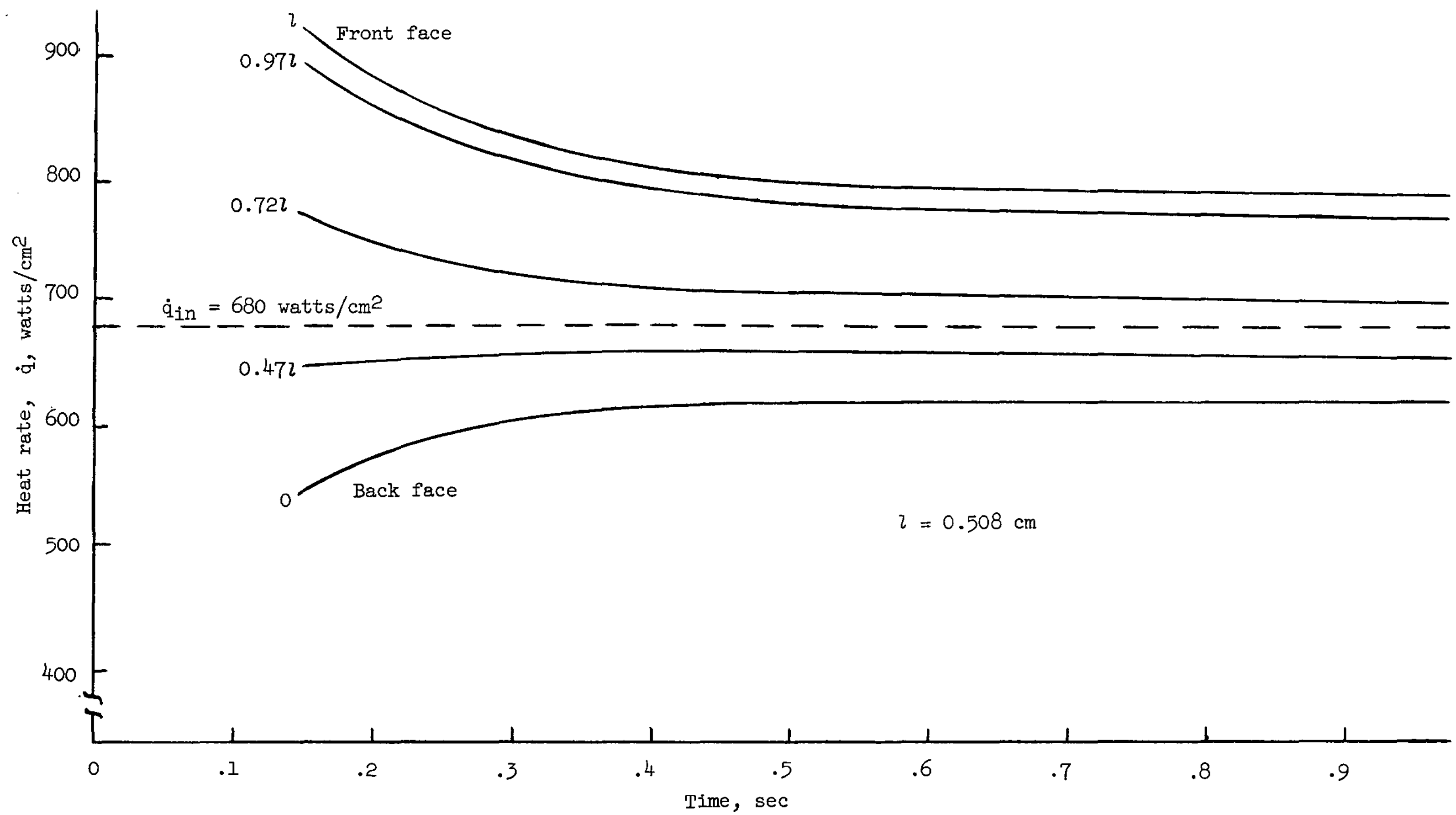


Figure 2.- Variation of calculated $\dot{q}$ with time at various locations in a beryllium calorimeter.

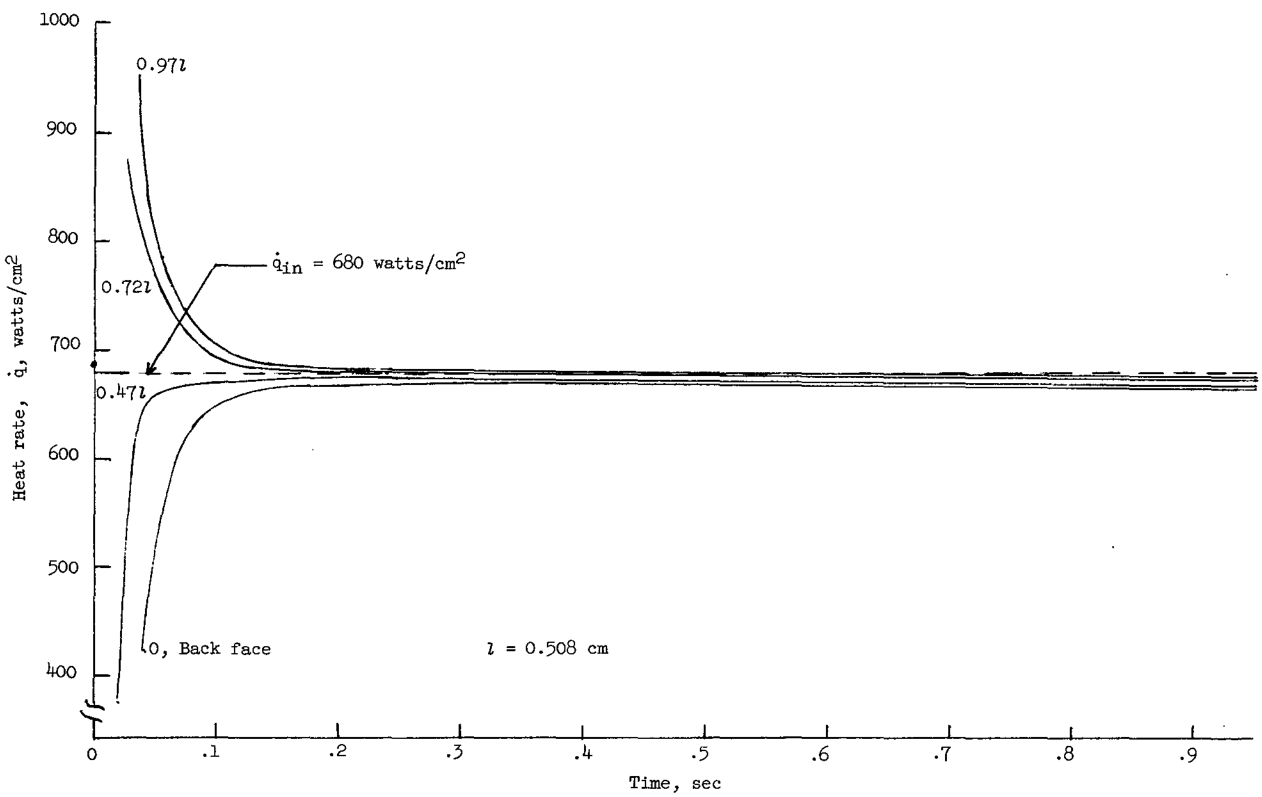


Figure 3.- Variation of calculated $\dot{q}$ with time at various locations in a copper calorimeter.

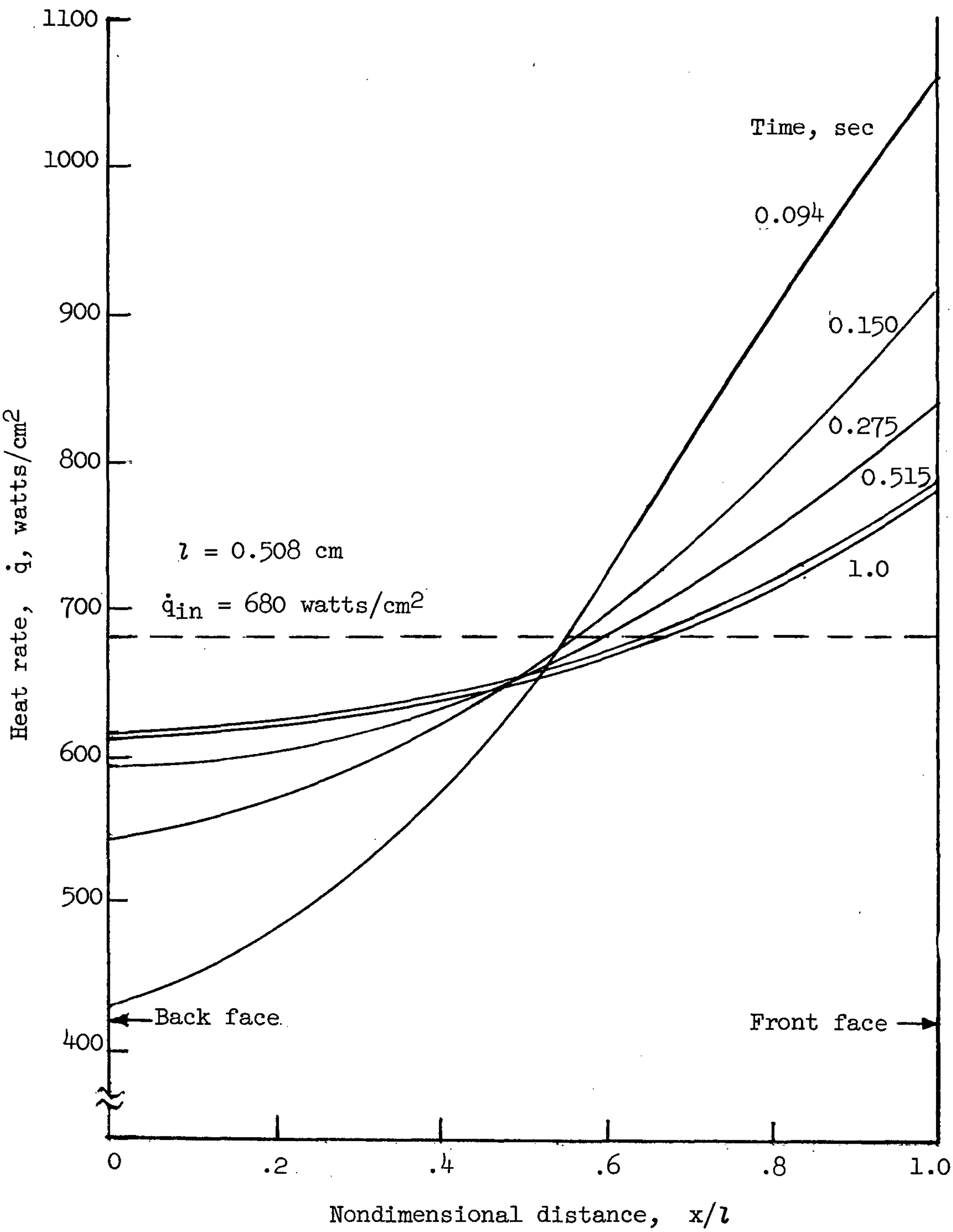


Figure 4.- Variation of calculated $\dot{q}$ with depth in a beryllium calorimeter at various times.

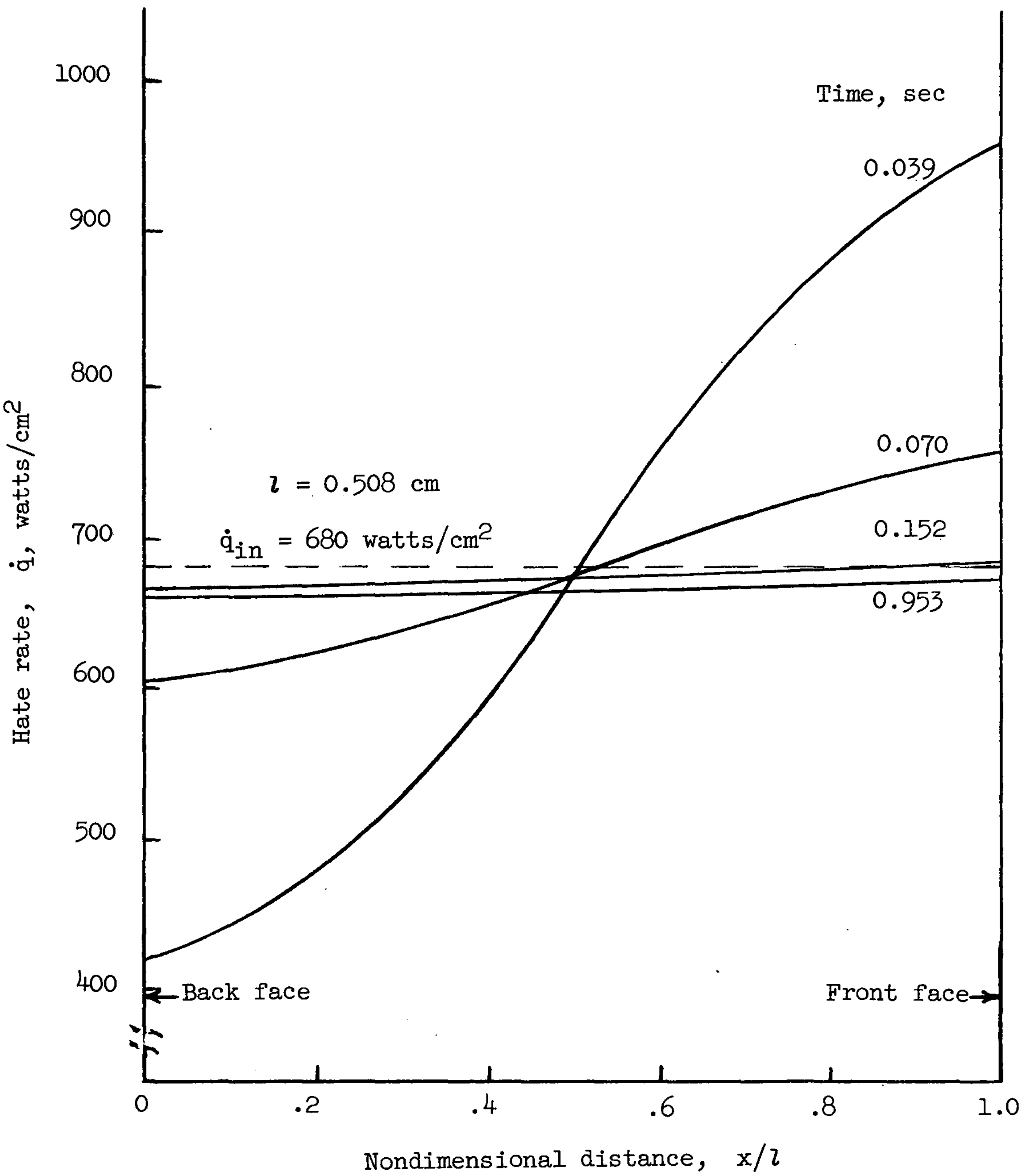


Figure 5.- Variation of calculated $\dot{q}$ with depth in a copper calorimeter at various times.

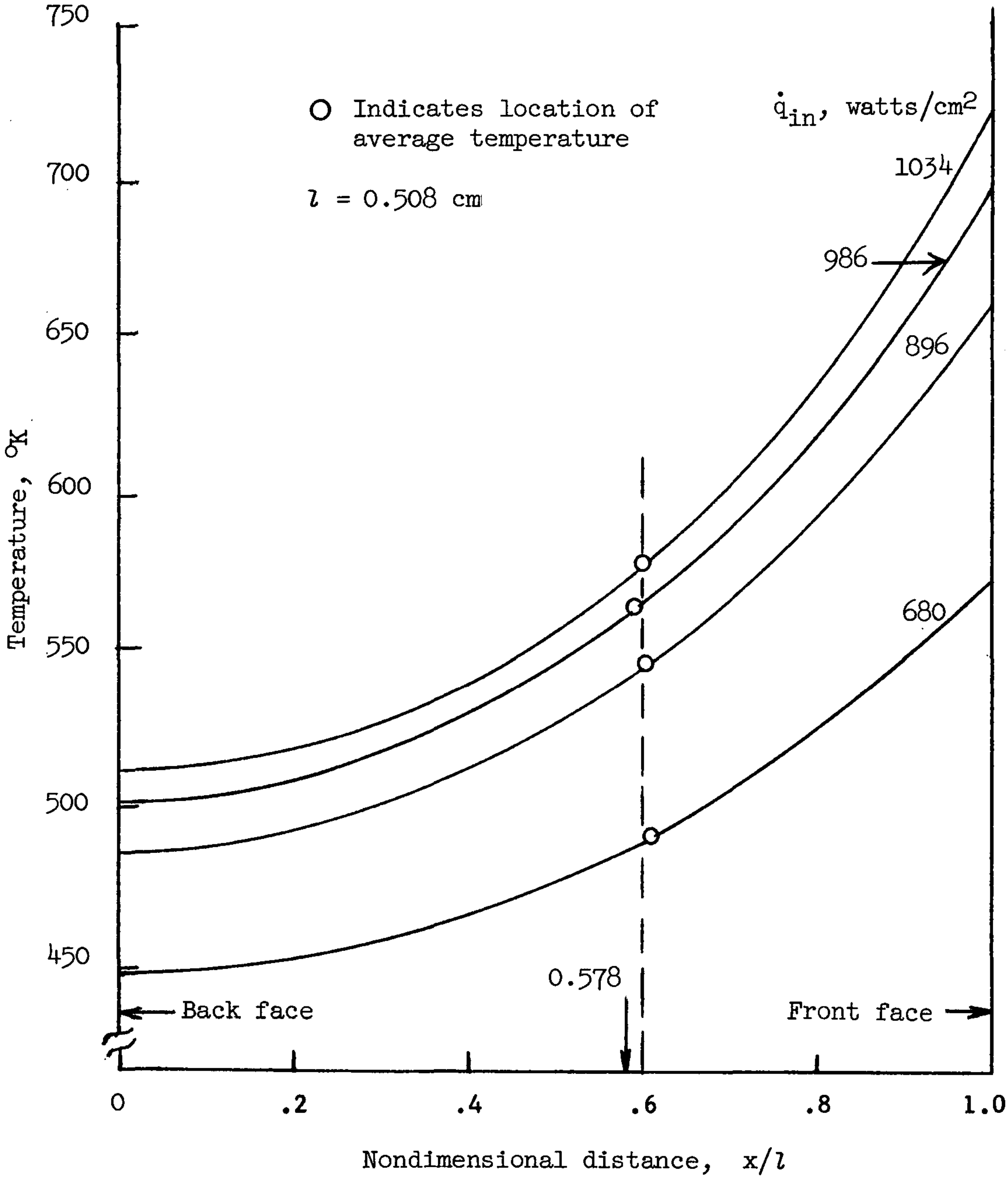


Figure 6.- Calculated temperature gradients in a beryllium calorimeter at 0.578 second for various values of $\dot{q}_{in}$.

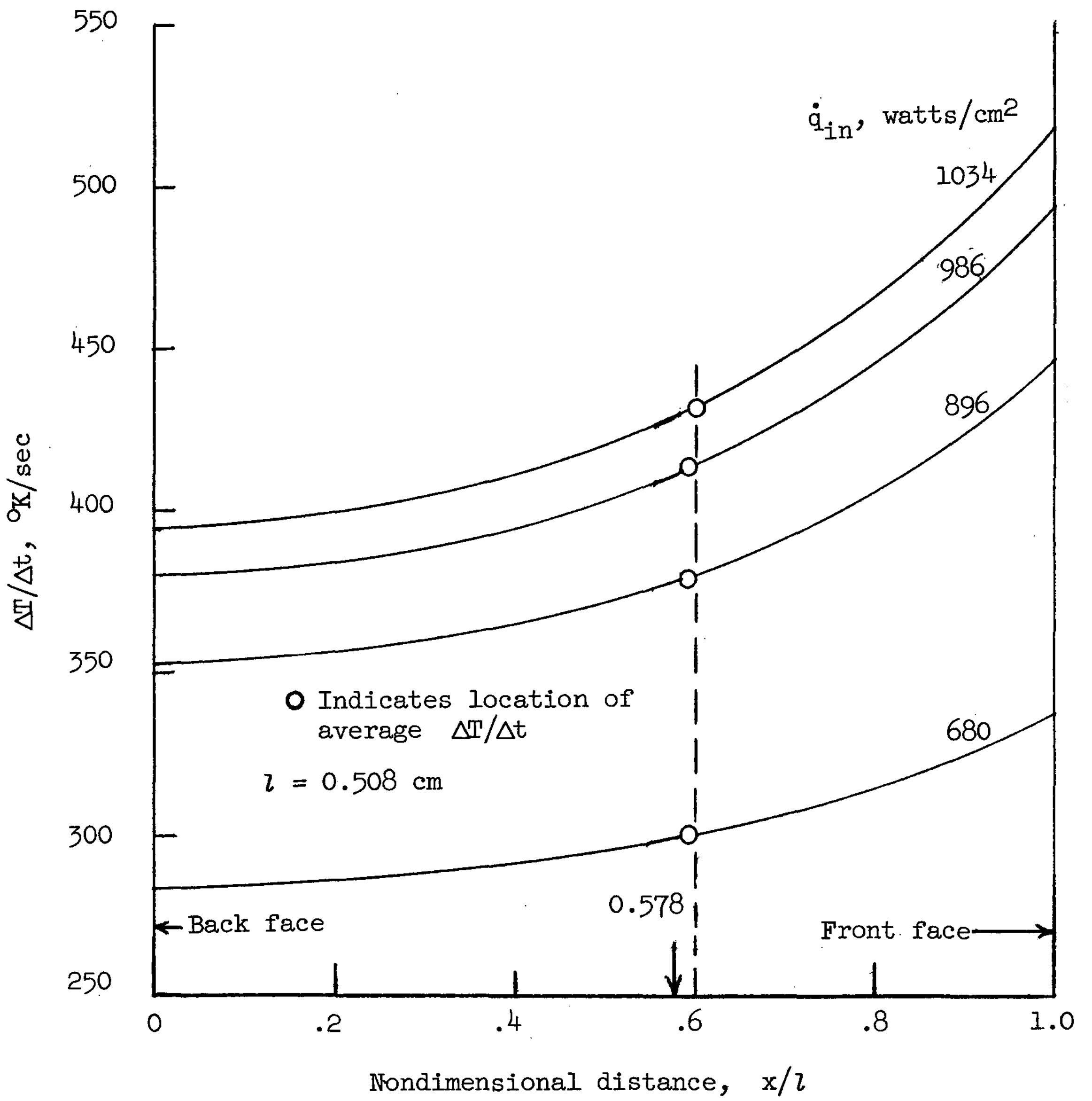


Figure 7.- Variation of calculated $\Delta T/\Delta t$ with depth in a beryllium calorimeter at 0.578 second for various values of $\dot{q}_{in}$.

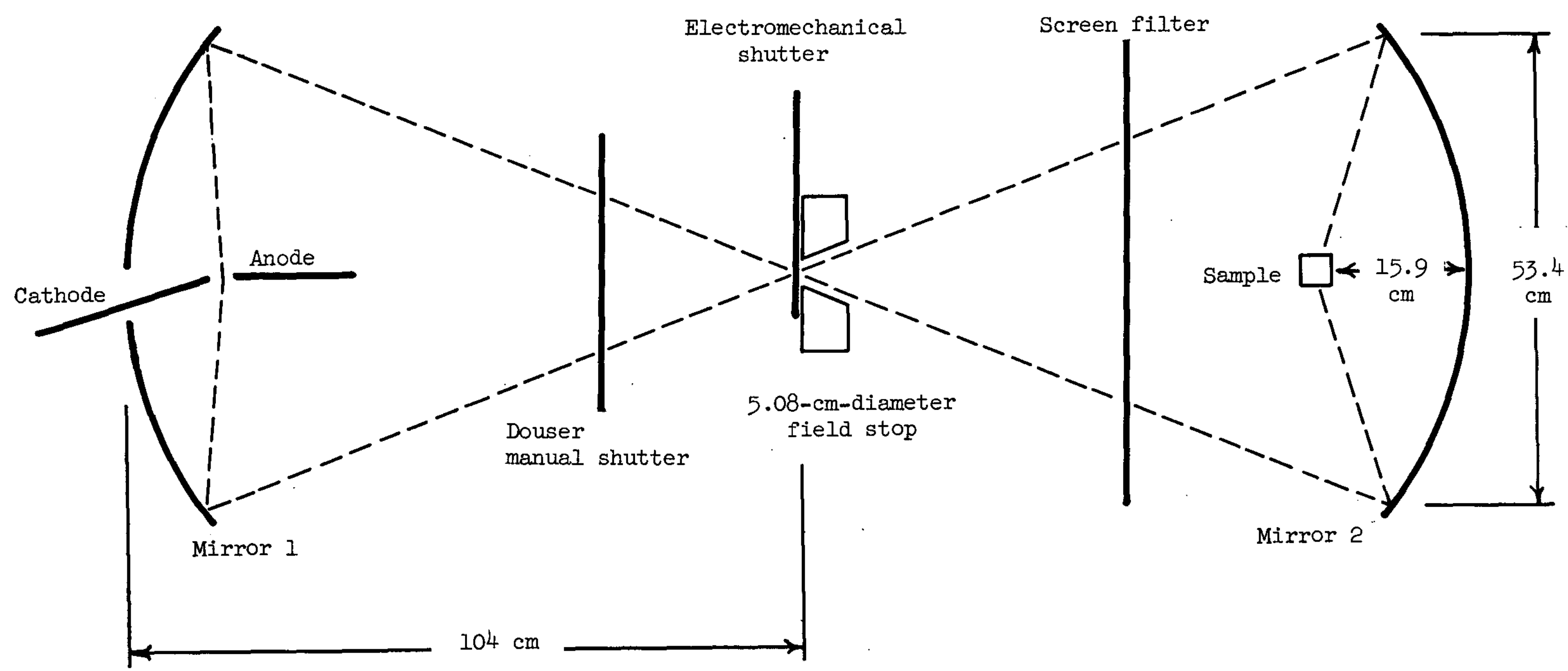


Figure 8.- Arc imaging furnace setup for calorimeter testing.

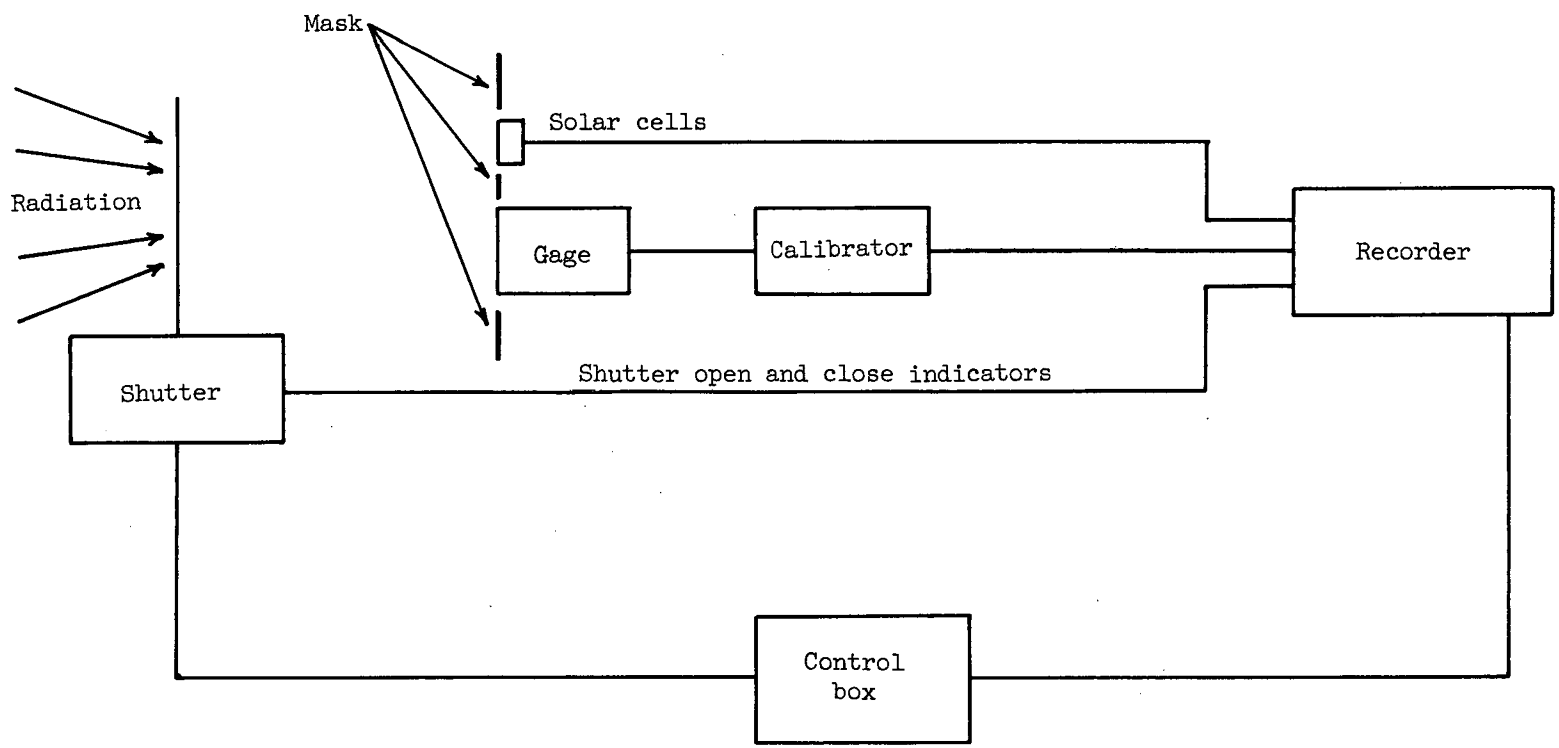


Figure 9.- Block diagram for calorimeter testing.

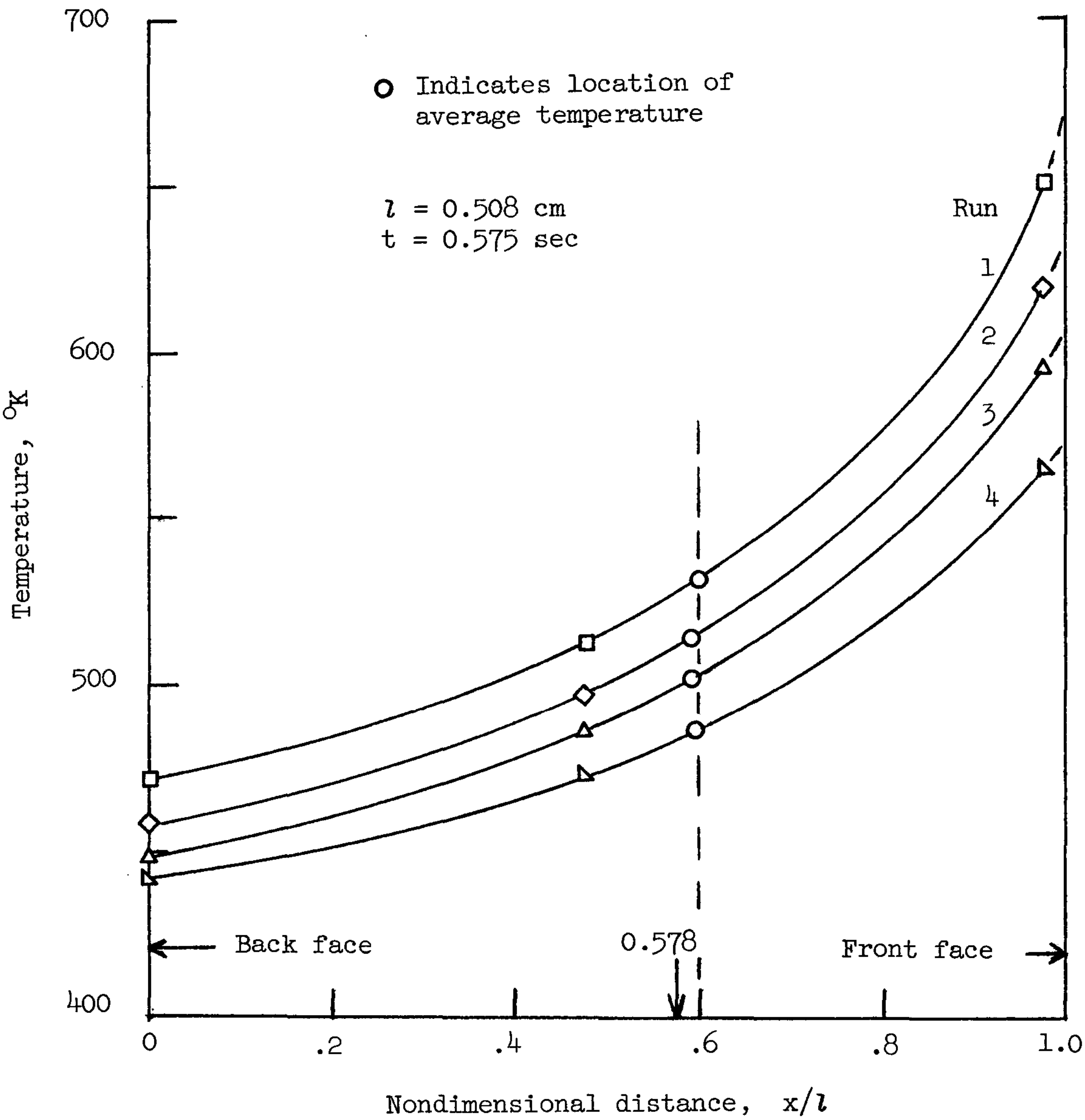


Figure 10.- Temperature gradients in a beryllium calorimeter for runs 1, 2, 3, and 4 with corresponding inputs of 845, 760, 705, and 635 watts/cm^2.

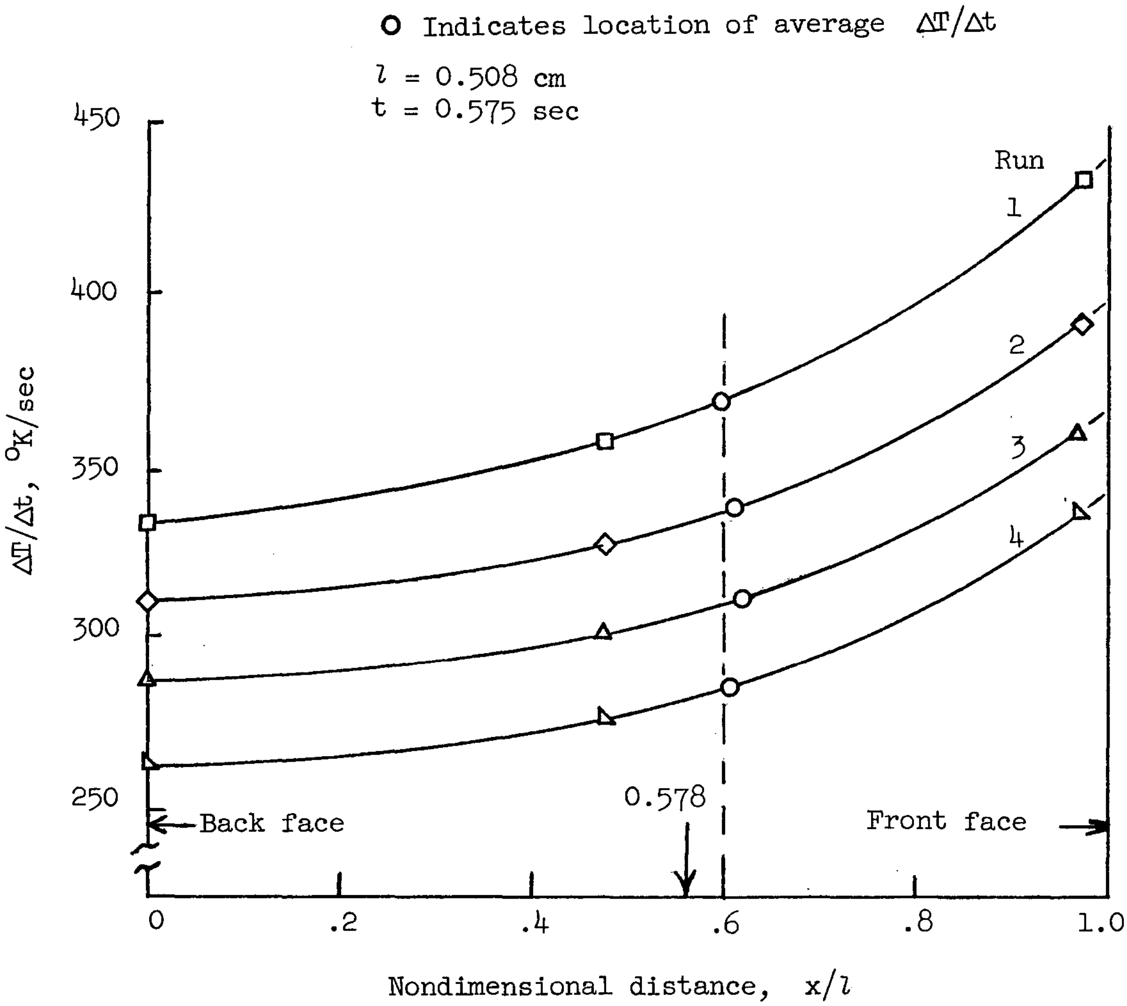


Figure 11.- Variation of $\Delta T/\Delta t$ with depth in a beryllium calorimeter for runs 1, 2, 3, and 4 with corresponding inputs of 845, 760, 705, and 635 watts/cm^2.

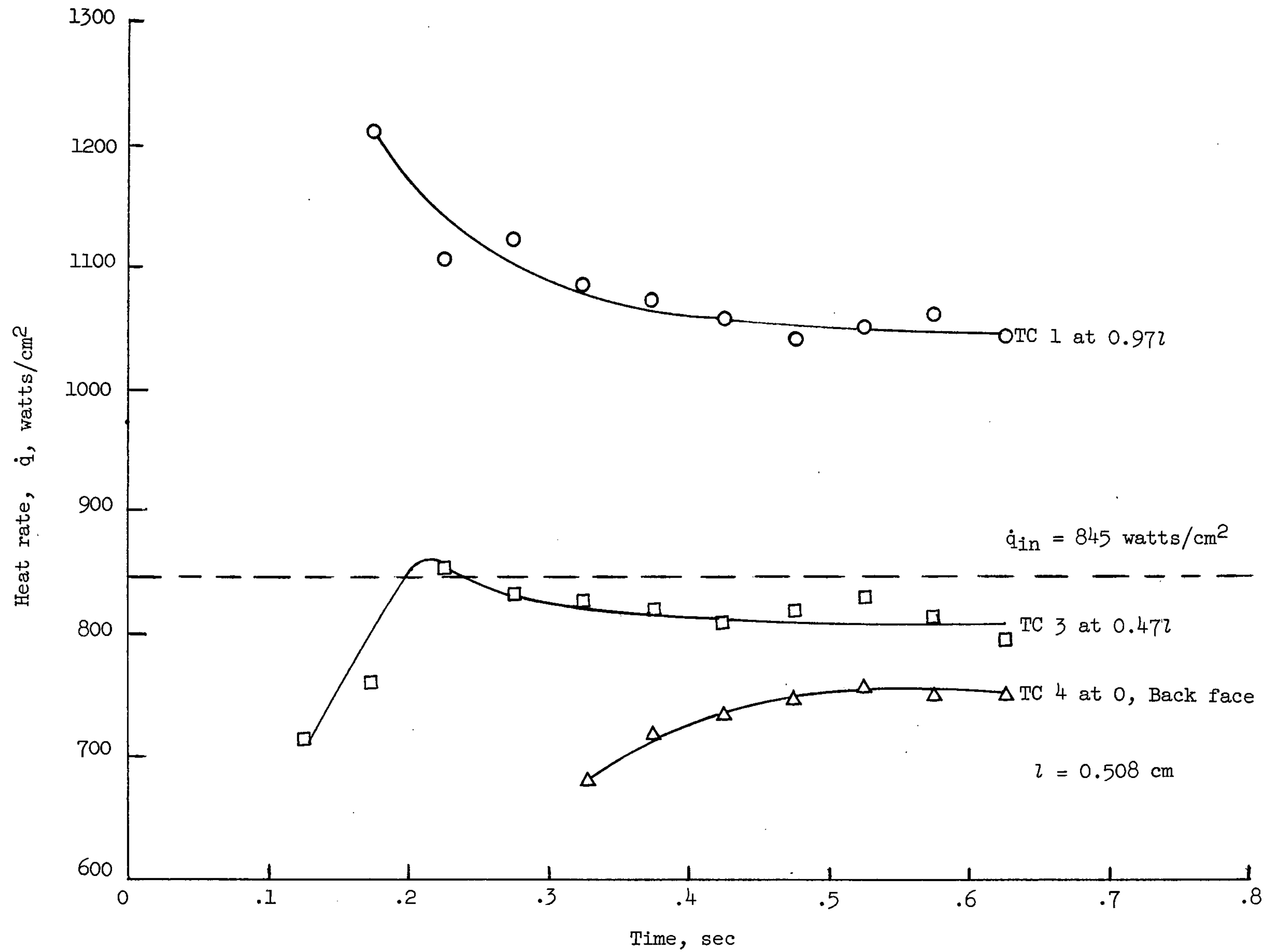


Figure 12.- Variation of measured $\dot{q}$ with time for run 1.

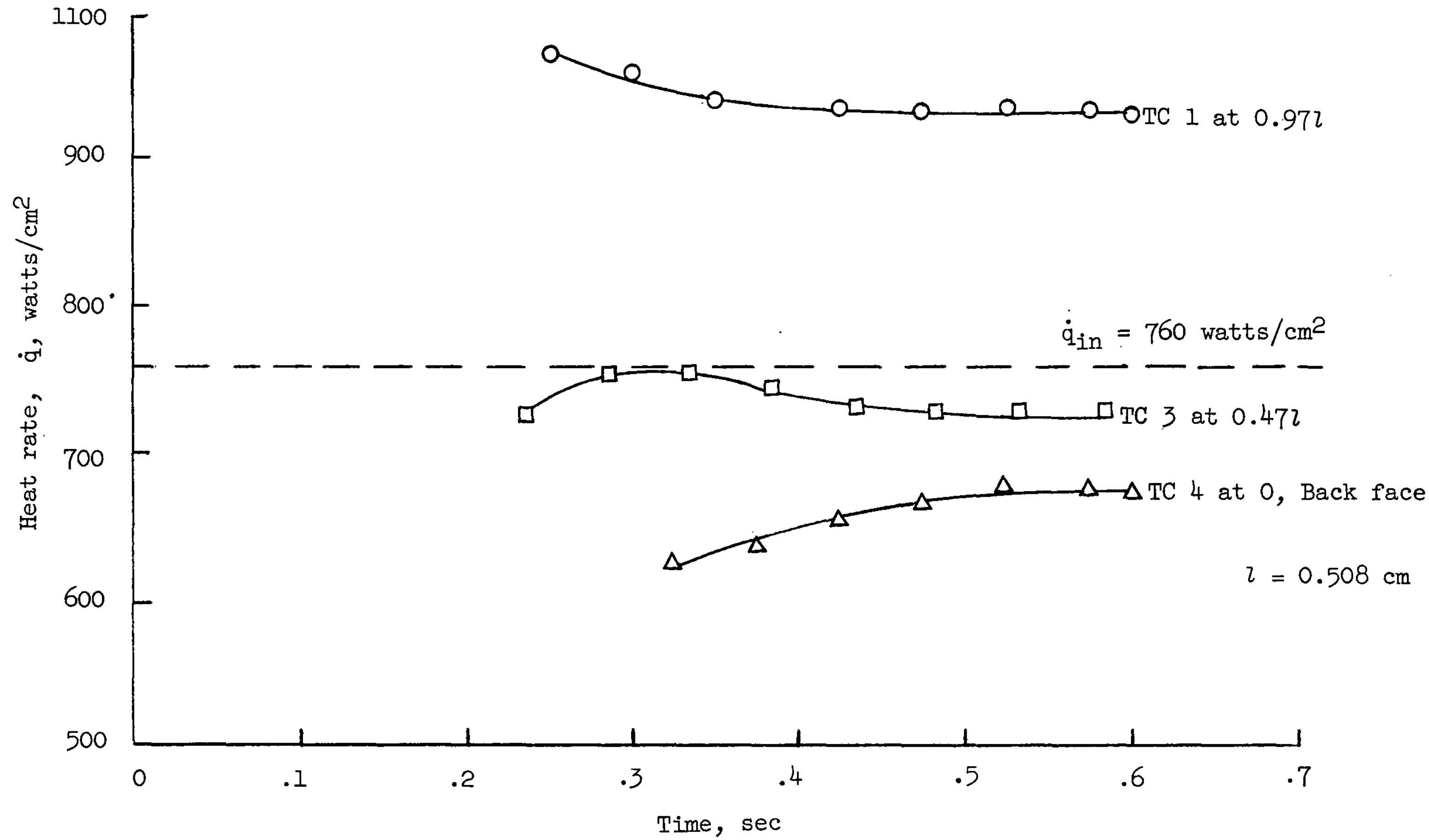


Figure 13.- Variation of measured $\dot{q}$ with time for run 2.

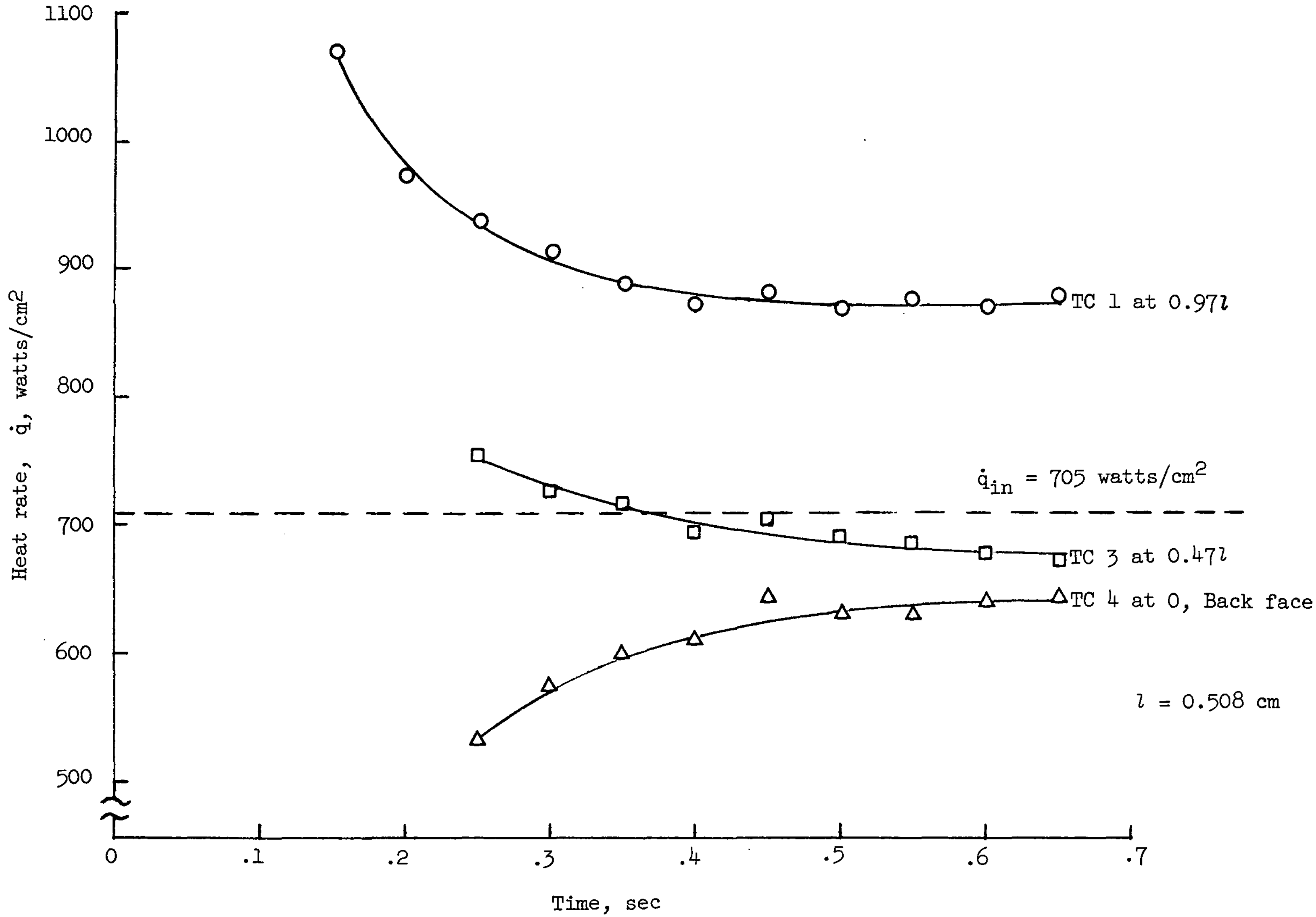


Figure 14.- Variation of measured $\dot{q}$ with time for run 3.

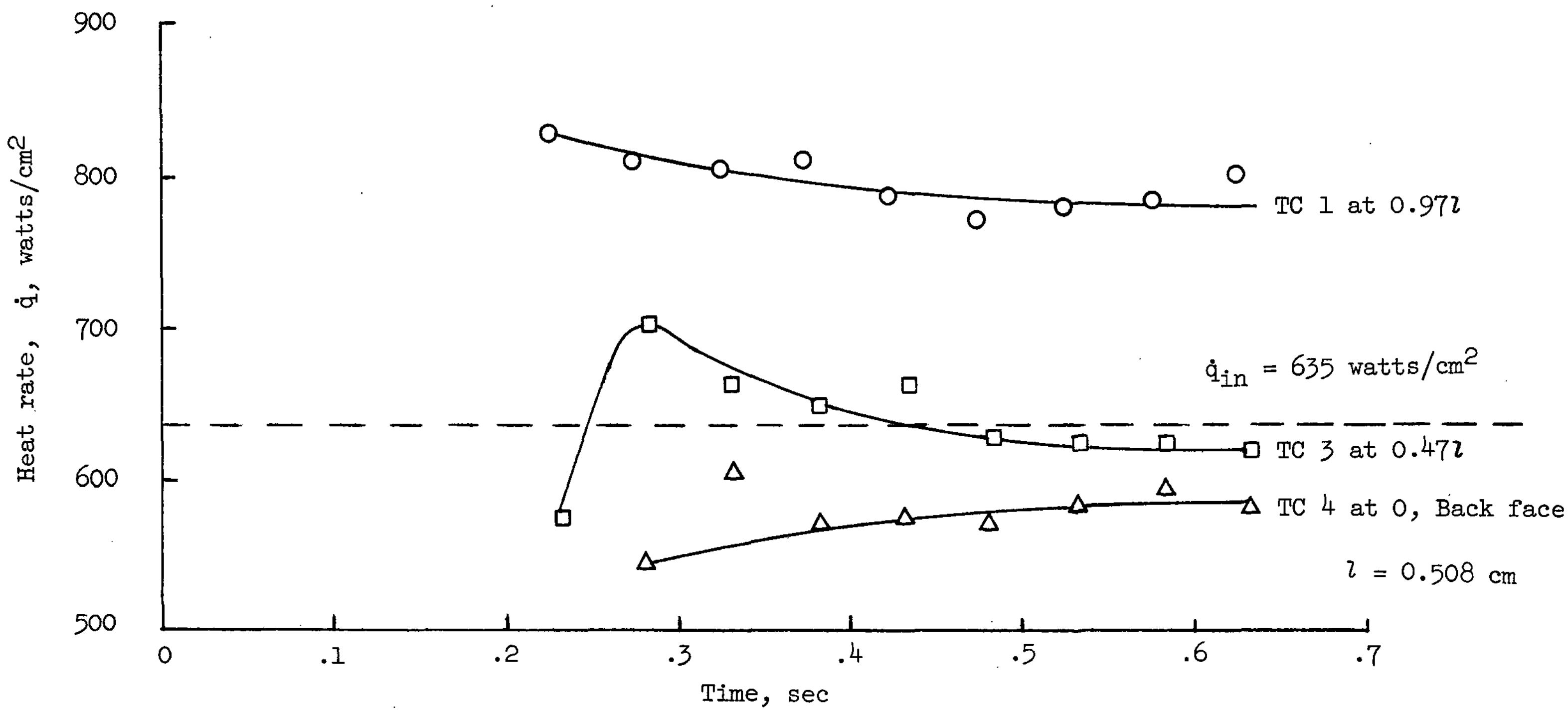


Figure 15.- Variation of measured $\dot{q}$ with time for run 4.

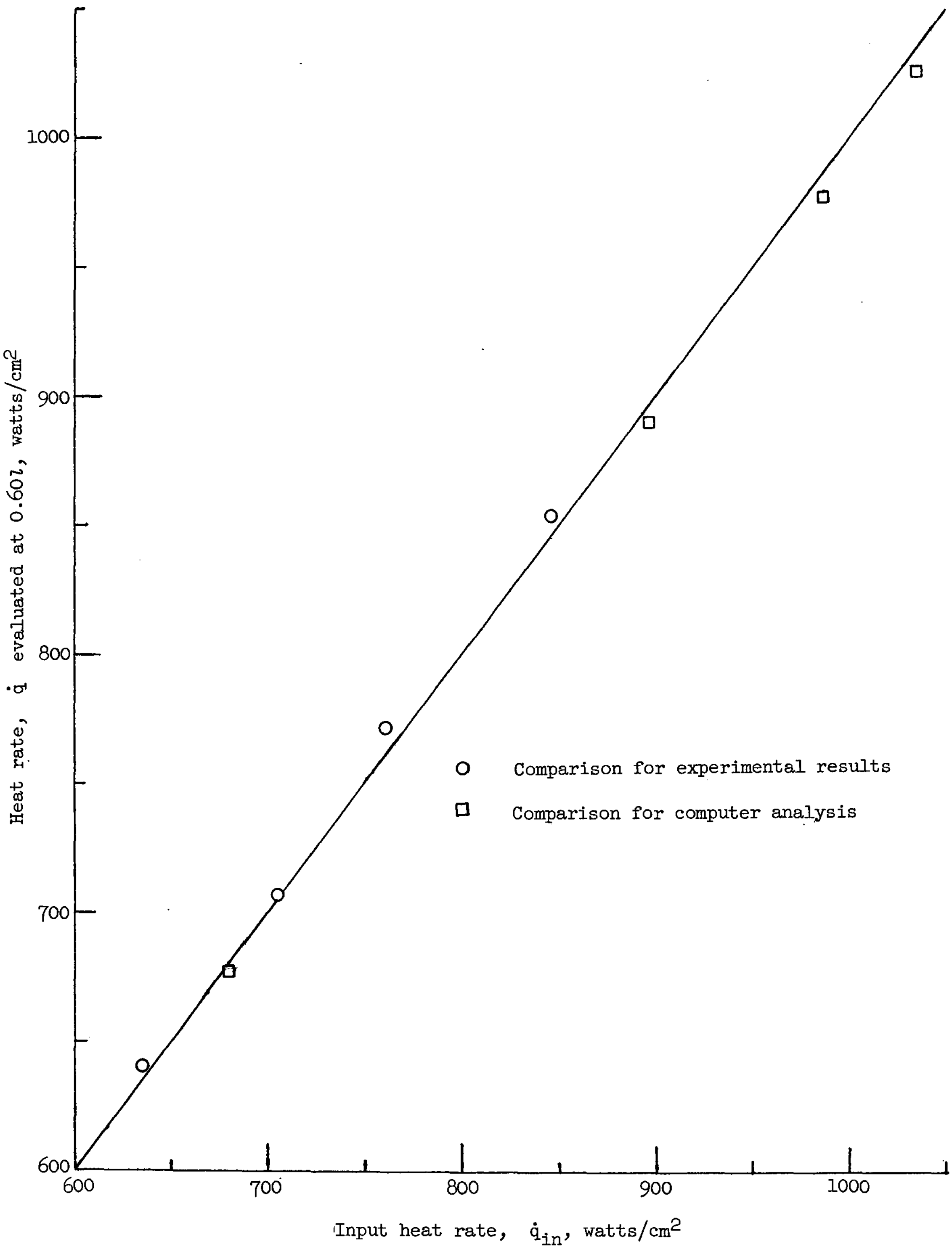


Figure 16.- Comparison of evaluated $\dot{q}$ at 0.60l location to the input $\dot{q}$ for a beryllium calorimeter at 0.575 second.

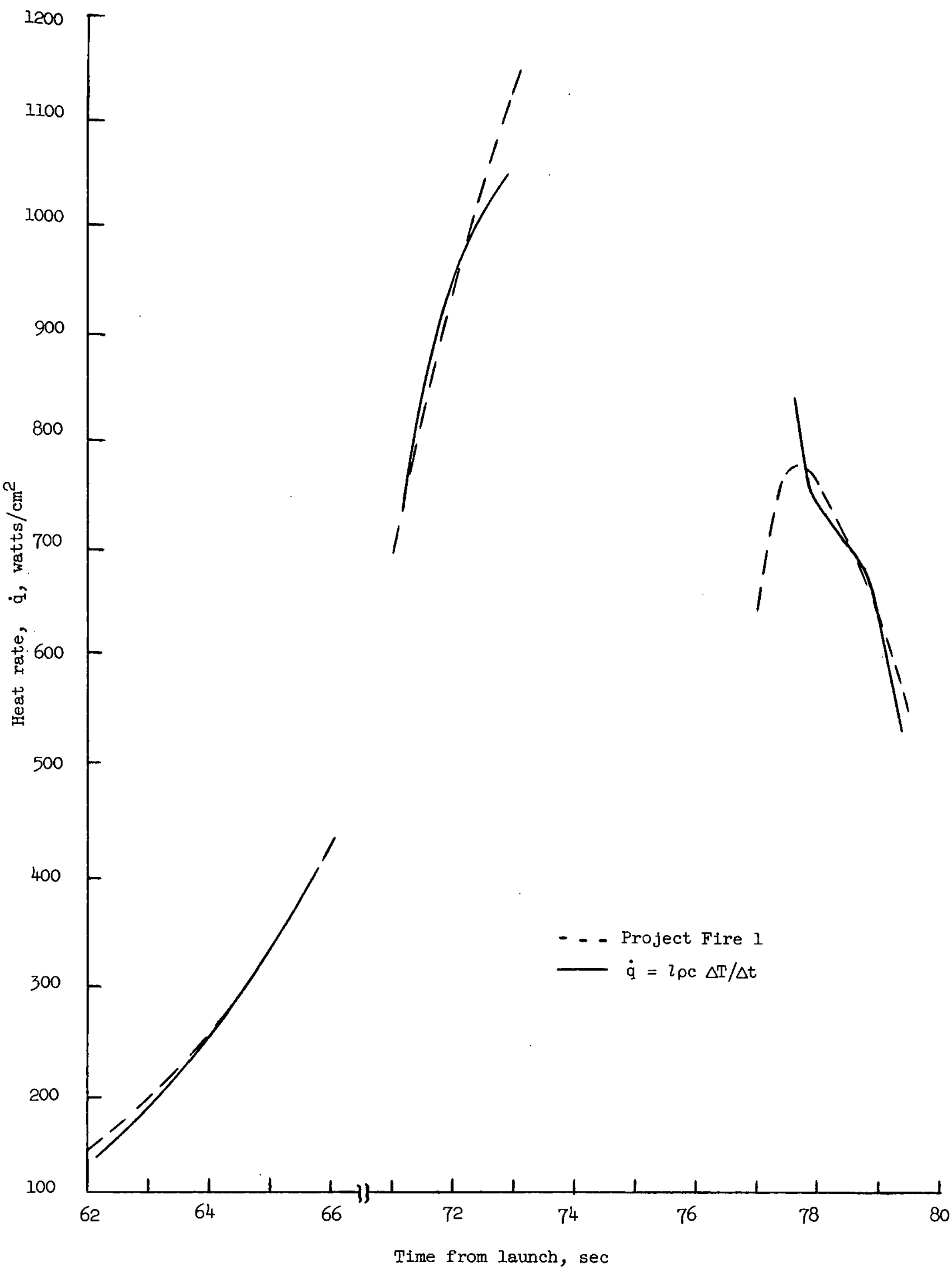


Figure 17.- Comparison of "inverse method" used by Project Fire 1 and simple method at $0.60l$ for determining input heat rate.